A Comparison of Different Means to Increase Daily Range of Electric Vehicles

The Potential of Battery Sizing, Increased Vehicle Efficiency and Charging Infrastructure

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Abstract—The limited range of plug-in electric vehicles – both battery and plug-in hybrid electric vehicles – is a crucial factor of the vehicles’ utility and user acceptance. We compare the impact of three means to increase the effective range an electric vehicle can drive during one day: the size of the battery, the vehicle’s efficiency in terms of electricity consumption per kilometer and recharging between trips using public charging infrastructure. As means to increase efficiency, we analyze variations of the vehicle mass, the impact of regenerative braking and a lower aerodynamic drag. The efficiency of the vehicles powertrain is assumed constant. We use real-world driving profiles to simulate individual driving behavior and real-world fuel and electricity consumption. Our findings indicate that weight reduction and an increased battery capacity offer noteworthy potentials to reduce electricity consumption and to increase the share of vehicles that could cover all their daily driving with a BEV.

Keywords—Electric vehicle; Driving Range; Efficiency Technology; Battery; Charging Infrastructure

I. INTRODUCTION

Electric vehicles (EVs) are a promising option to decarbonize the transport sector [1]. Countries worldwide have set EV fleet targets to foster EV market introduction. Nevertheless, the share of EVs in sales and stock is still limited and many potential buyers are skeptical about an EV’s utility. A major hindrance in EV acceptance is the limited electric driving range of EVs [2]. Different means are possible to increase the driving range of EVs: (1) battery capacity could be enlarged, (2) EV fuel efficiency could be increased to drive longer distances per day with fixed battery capacity and (3) charging infrastructure could be used to re-charge EVs during stops. These means increase the distance that could be driven with a battery electric vehicle (BEV) during one day. While a higher battery capacity implies a greater gross vehicle weight and thus a negative effect on vehicle efficiency, a dense fast charging infrastructure could render high battery capacities unnecessary, thus potentially averting costs and production emissions for an oversized battery. As effects on vehicle efficiency, the impact of the vehicle mass and the aerodynamic drag are analyzed. Additionally, the effects of regenerative braking on total vehicle consumption are analyzed. Here, two different efficiencies for regenerative braking are considered, regardless of the vehicle’s powertrain. A more efficient powertrain is not considered here, but will be part of further research. Clearly, the different means to increase daily driving range cannot be analyzed separately when trying to determine an economic optimum between the measures to increase driving range. Vehicle fuel consumption and hence the effects of the different means on daily driving range depend on the individual user’s actual driving style. Users differ widely both in the daily distances driven and the regularity of distances driven but also in their individual fuel consumptions. The large variation in specific fuel consumption between individual users is determined by the average vehicle speed (inner city driving or highway), by the specific terrain (flat or hilly) and also by the driver’s aggressiveness (high or low acceleration, frequent or infrequent braking). A recent analysis of thousands of real-world driving profiles shows that actual fuel consumption significantly deviates from driving cycle fuel consumption and strongly varies (up to 50%) between users of the same vehicle model [3]. Thus, real-world driving data should be used for reliable estimates of fuel consumptions and a systematic comparison of means to increase the daily driving range of EVs.

The aim of this paper is to compare and evaluate the options battery sizing, vehicle efficiency and charging infrastructure with regard to their potential to increase driving range for real driving profiles while minimizing total cost. Costs are evaluated as total costs of the options, not differentiated by where they occur (for the user, for the automaker or for a charging infrastructure provider). Initially, a reference driving range for a set of driving profiles is determined by modeling driving forces.

The paper is structured as follows. Sections II and III describe data collection of driving profiles and the underlying costs, respectively. System modeling is presented in section IV, in section V results are shown, validated and discussed. The paper closes with a short outlook on future extensions of the model in section VI.

II. DATA: COLLECTION OF DRIVING PROFILES

To analyze the potential to increase daily driving range of electric vehicles, real-world driving profiles are necessary. We have been collecting data on commercial traffic of conventional vehicles with a time horizon of 21 days [4] in the ongoing project REM 2030. Data are collected by GPS-tracking. The dataset contains 440 driving profiles with an
average of 69.9 vehicle kilometers travelled (VKT) per day. With a total number of 49,331 trips, the dataset is comparable to other datasets on driving behavior. In the publicly available data [4], trips are reported aggregately. However, for the modeling of driving forces (see section III) data with a higher temporal resolution is required. The recorded raw data of the above mentioned dataset is appropriate (at the time of writing, raw data is available for 111 of the aforementioned 440 driving profiles, see Table 1). At least every 500 meters a data point was recorded containing the parameters listed in Table 2. Every data point is assigned with a unique ‘signal_id’. The ‘beacon_id’ represents the International Mobile Station Equipment Identity (IMEI), identifying the used GPS-data logger. The main parameters used for the generation of driving profiles are the time stamp (‘added_at’) and the velocity (‘speed_km’) to model the time and velocity vectors. The data on ‘dec_lat’ and ‘dec_long’ describing geographical location can be used in further work for extensions of the model.

### TABLE I. Specification of the Driving Profiles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data collection Design</td>
<td>GPS-tracking</td>
</tr>
<tr>
<td>Total number of profiles</td>
<td>111</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1 data point every 50 sec.</td>
</tr>
</tbody>
</table>

### TABLE II. Driving Profile Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>‘signal_id’</td>
<td>Unique for each data point</td>
</tr>
<tr>
<td>‘beacon_id’</td>
<td>IMEI of the data logger</td>
</tr>
<tr>
<td>‘added_at’</td>
<td>Time stamp</td>
</tr>
<tr>
<td>‘speed_km’</td>
<td>Velocity in km/h</td>
</tr>
<tr>
<td>‘dec_lat’</td>
<td>Latitude; geographic coordinate</td>
</tr>
<tr>
<td>‘dec_long’</td>
<td>Longitude; geographic coordinate</td>
</tr>
</tbody>
</table>

Metadata of the driving profiles are also available. These data contain information about company size, economic sector of the company that owns the car and car size. In the simulation only car size information is used.

### III. Cost Parameters

Assumed costs for the aforementioned economic comparison of the analyzed measures are presented in the following. Costs are compared for the reference years 2015 and 2020. The technical parameters of the three measures are considered as constant.

### IV. System Modelling

#### A. Data processing

The data mentioned in section II is used to create driving profile vectors $d$ with a normalized time-vector starting with $t_0 = 0$ and the corresponding velocity vector. The driving profile vector serves as input for the driving model as well as the information about car size. For the different car size categories reported (compact, medium-sized, luxury cars and transporters) a separate car model is used. We calculate driving forces in a quasi-static model as described in the following section.

#### B. Modelling of driving forces

Driving forces have to be overcome to move a vehicle. Our presentation and calculation of driving forces follows [7]. The total driving force $F_D$ is given by the sum of aerodynamic drag force $F_{air}$, rolling resistance $F_r$, acceleration resistance $F_a$ and hill climbing force $F_g$:

$$ F_D = F_{air} + F_r + F_a + F_g $$

In this paper hill climbing force is not being considered in accordance to testing conditions of official reference cycles like the European Driving Cycle (NEDC). Given this and inserting explicit expressions [7] for the forces in (1) results in

$$ F_D = 1/2 \, c_a \, \rho \, A \, v^2 + \mu \, m \, g + m \, a $$

The efficiencies of the vehicle components, e.g. the drive chain and the motor, have to be implemented to calculate motor engine power. We assume a static characteristic of the components as well as uniform motion. Thus the electric vehicle can be completely represented by the parameters front surface ($A$), air resistance coefficient ($c_a$), one lumped mass ($m$), the rolling resistance coefficient ($\mu$) and total vehicle efficiency ($\eta$). The gravitational field strength $g = 9.81 \, \text{m s}^{-2}$
and air density $\rho = 1.205 \text{ kg m}^{-3}$ are assumed to be constant. This allows for an efficient computation. Finally, mechanical power $P_D$ is calculated from the driving force by

$$P_D = 1/\eta F_D v$$ (3)

The power demand of auxiliaries is presumed constant. For the comparison of the results, power demand for auxiliaries is set to zero. Additionally for the same reason, mass variation due to passengers is not included.

Parameters of the four reference vehicles are shown in Table IV.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification of vehicle type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Compact</td>
</tr>
<tr>
<td>Vehicle Mass [kg]</td>
<td>1200</td>
</tr>
<tr>
<td>Mass of Inertia Tensor [-]</td>
<td>1.15</td>
</tr>
<tr>
<td>Air Resistance Coefficient $c_w$</td>
<td>0.33</td>
</tr>
<tr>
<td>Front Surface Area [m$^2$]</td>
<td>2.04</td>
</tr>
<tr>
<td>Rolling Resistance Coefficient $\mu^r$</td>
<td>0.015</td>
</tr>
<tr>
<td>Drive Chain Efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Motor Efficiency (Constant)</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery Efficiency</td>
<td>0.9</td>
</tr>
<tr>
<td>Total Vehicle Efficiency $\eta$</td>
<td>0.73 (= 0.9 * 0.9 * 0.9)</td>
</tr>
<tr>
<td>Regenerative Braking Efficiency</td>
<td>0.2/0.3</td>
</tr>
<tr>
<td>Battery Capacity [kWh]</td>
<td>20</td>
</tr>
<tr>
<td>Maximum Depth of Discharge</td>
<td>0.9</td>
</tr>
<tr>
<td>Battery Mass [kg]</td>
<td>190.5</td>
</tr>
</tbody>
</table>

C. Modelling of Battery Capacity and Calculation of Technical Potential

The different components of the vehicle are modeled as Matlab® classes, as well as the information about the driving profiles. The battery state of charge (SOC) is modeled such that it decreases linearly with the energy needed for the propulsion. The SOC decreases linearly with cumulated energy consumption regardless of the technical feasibility. That is no threshold for the SOC is implemented in the model. Thus the SOC can have negative values and has to be seen as a theoretical value. As driving profiles are recorded by conventional cars, reported distances can be too long to be made by a BEV, thus leading to a negative SOC. As a result, the technical potential of a driving profile to be possibly done by a battery electric vehicle is given, if and only if the SOC does not take negative values during the battery simulation. In other words, the daily range of the driving profile (including intermediate recharge if charging infrastructure is available) is below the assumed range of the electric vehicle. We assume that the battery is fully loaded at the beginning of the simulation.

D. Modelling of Charging infrastructure

For all driving profiles the possibility to charge at home or at the company ground respectively, is presumed. Due to missing data on trip purposes, we assume for simplicity that overnight or work charging can be applied when the vehicle stands still for at least six hours, i.e. when the difference between two consecutive data points exceeds this time span. Charging power of home and work charging is 3.7 kW. As a potential alternative to a higher battery capacity or higher vehicle efficiency, public fast-charging infrastructure is applied as a mean to enlarge the driving range. In this work, public charging with a power of 22 kW can be applied in every vehicle parking period longer than 30 minutes. Battery swapping is not regarded as an option as its realization is questionable [15].

E. Statistics

Each user’s individual driving behavior is analyzed and the user-specific average fuel consumption is calculated (averaged over his or her whole driving). We thus obtain many individual average specific energy consumptions and accordingly many specific driving ranges. We use a kernel density estimate with optimized band width according to [16] to analyze the underlying distribution of fuel consumptions. 95%-confidence bands for probability density have been obtained via standard bootstrapping (see [17] for details).

V. RESULTS AND DISCUSSION

A. Technical effects

Fig.1 shows the distribution of the calculated average fuel consumptions. The average fuel consumption in kWh per 100 km is plotted on the abscissa; the ordinate shows the probability density for the respective consumption value. For the calculation, the four car sizes compact, medium-sized, luxury car and transporter are assumed. The assignment to the driving profiles is according to the reported metadata (section II). Specifications are given in Table IV. The blue curve shows the distribution of energy demand with an overall efficiency of regenerative braking of 30%, while the black curve shows the results for an according efficiency of 20 %. Overall regenerative braking efficiency here refers to the amount of energy usable for driving as fraction of the theoretical value of the mechanical energy resulting from a negative acceleration (force). The graphs show a peak at ca. 15 - 20 kWh/100 km...
with the blue curve (higher regenerative braking efficiency) being slightly shifted to lower values. The dashed lines indicate 95% confidence bands.

![Distribution of Energy demand](image1)

**Fig. 1.** Energy demand depending on regenerative braking efficiency.

![Distribution of Energy demand](image2)

**Fig. 2.** Energy demand for different means.

![Technical potential of fast charging compared to a larger battery](image3)

**Fig. 3.** Technical potential of fast charging compared to a larger battery.

The low simulated consumption values smaller than 10 kWh/100km can be explained by the fact that the hill climbing force and the auxiliaries’ power demand have been neglected. Figure 2 shows a comparison of the influence of different means on average vehicle consumption. The high influence of the vehicle mass on consumption can be clearly seen, the consumption density curve is significantly shifted to lower values when the vehicle weight decreases. It is also interesting to note that the curve for a lower aerodynamic drag is compressed in comparison to the other means. Probably part of this effect is due to the high influence of the aerodynamic drag on vehicle consumption for high velocities. Assuming that the driving profiles with a high average consumption are driven at a higher speed on average than driving profiles with a lower average consumption, potential savings resulting from optimized aerodynamics are disproportionally higher for the latter thus resulting in a compressed distribution of the resulting average consumption values compared to the reference case. However, the non-linear influence of the velocity augments the complexity of the analysis. Further research to verify the assumption is needed.

Figure 3 shows the technical potential of fast charging infrastructure compared to battery capacity increase. The graph can be read as follows: 11% of all driving profiles could be replaced by BEVs with all their trips. This technical potential is positive if all distances driven between two recharging events are below the technical range of the respective car (for the modeling of charging infrastructure see section IV.D). Thus, 11% of all vehicles can be replaced by BEVs and perform all their daily driving. When adding fast-charging infrastructure and keeping the battery size fixed, the technical potential increases by about 10%. When instead of fast-charging infrastructure the battery capacity is increased, an increase to 140% of the reference battery capacity is needed to reach the same increase of the technical potential by 10%. For the sample, an increase of the battery capacity by 40% equals a weighted average of 5 kWh. Above a battery capacity of 130% of the reference size, the technical potential of the sample increases only slightly for higher battery capacities. In total, a technical potential of over 35% can be reached with a high battery capacity and a dense fast charging infrastructure.

### B. Validation

In this section, the model is validated. The model is tested with the New European Driving Cycle (NEDC) and the results are compared to official data on the fuel consumption of vehicles equivalent to the reference vehicles used in the simulation (see Fig. 4). For the three reference vehicles, compact, mid-sized and luxury car, we get an electric consumption of 11.4, 14.0 and 17.1 kWh/100 km, respectively. These values are very close to the official consumption values of the following vehicles (Table V). An Audi A11.4 TFSI, the vehicle comparable to the reference compact car, officially consumes 5.3 l Super petrol per 100 km [18]. Given the density of Super petrol with 8.8 kWh/l [19] and an overall estimated efficiency of a conventional vehicle of 25% [20], this results in an electric consumption of 12.9 kWh/100 km.

\( k \) Battery capacity as percentage of reference battery capacity. For the different car sizes different battery capacities are used, as shown in Table IV.
For a Volkswagen Passat TSI Blue Motion we get 5.9 l/100km [21] or 14.3 kWh/100 km and for a Mercedes-Benz S 500 we get 8.6 l/100km [22] or 20.9 kWh/100 km, respectively.

C. Economic comparison

In this section we compare the technical potential of the different means (see section V.A) to their investment costs (see section III). In a first step we compare investments for the different means and not the total cost of ownership (TCO) to the individual users. While a higher battery capacity will lead to higher electricity consumptions and thus higher operational costs due to higher battery weights, efficiency measures that lower consumption directly will lead to lower operational costs. When looking at the comparison between the construction of public charging infrastructure and a higher battery capacity, the latter one seems to be the cheaper option. Costs for a public fast charging point are around seven times higher than for an additional battery capacity of 5 kWh. As battery and infrastructure cost decrease in a similar proportion, this holds for both reference years 2015 and 2020. i.e. a charging point has to serve seven EVs when being operated economically in comparison to a higher battery capacity, assuming comparable operational costs1. Especially at the beginning of the market ramp up for electric vehicles, a high utilization factor is questionable. In conclusion, simple economic arguments indicate that public fast charging infrastructure cannot be operated profitably, especially in comparison to higher battery capacities. These results are in accordance with [23, 24]. For the implementation of lightweight design a wide range of costs reaching from 2 to 18 Euro/kg have been reported [25]. A mass reduction of 200 kilograms thus would cost from 200 to 3,600 Euros. In total, a reduction of up to 450 kg per vehicle is possible [26], depending on the vehicle size and structure.

1 It is questionable whether a higher battery capacity will actually lead to additional operating costs of 1400 – 1800 Euro p.a. (see Table IV). Nevertheless, a higher battery capacity becomes even more attractive in comparison to the built up of public charging infrastructure to increase the effective range of electric vehicles.

VI. Conclusions and Outlook

We simulated the effect of three different means to increase the daily driving range of EVs for about 100 individual driving profiles. Our results indicate that weight reduction and an increased battery capacity offer noteworthy potentials to reduce electricity consumption and to increase the share of vehicles that could cover all their daily driving with a BEV. However, the total costs of weight reduction and battery size increase differ largely between individual users since the possible amortization of fuel efficiency measures depends on the individual user’s specific usage pattern and annual VKT. Public fast charging infrastructure also offers high potentials to increase the share of BEVs. However, the high investment costs limit the economic potential of this alternative. Future research should include hybrid plug-in EVs and differentiate between users with different annual VKT. Finally, geographical data could be used to model the availability of public charging infrastructure in more detail.

Acknowledgment

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References


